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Abstract

We propose that disruptive changes pertaining to complex product systems (CoPS) will yield a different set of characteristics than those traditionally observed for commodity products, and seek evidence for this proposition in a case study of the Flash Converting technology, a disruptive CoPS innovation in the copper production industry. Our results show that unlike disruptions in commodity product industries, the incumbent CoPS technology does not overshoot mainstream market performance demand. Also, the disruptive CoPS innovation; (i) is not nurtured in low-end niche markets, (ii) initially satisfies mainstream market performance demand, and (iii) has higher unit price than the incumbent technology.

Keywords: complex product systems, disruptive innovation, case study, copper production[1]

1. Introduction

CoPS (complex product systems) are customized, one-off or small batched capital goods items, which are high in complexity and value (Autio, Hameri, & Nordberg, 1996; Miller, Hobday, Leroux-Demers, & Olleros, 1995). Examples of CoPS include telecommunications systems, air traffic control systems, aircraft engines, offshore oil equipment, and weapon systems. Scholars who have advanced this literature propose CoPS to form a generic category of industrial products, distinct from mass-produced commodity products such as cars,

[1] An earlier version of this paper was presented at the 21st International Conference on Management of Technology (IAMOT) Conference, Hsinchu, Taiwan, March 18-22, 2012.

semiconductors, and consumer electronics (Hobday, 1998), and which can absorb a significant percentage of a nation's industrial investment (e.g. Barlow, 2000). Moody and Dodgson (2006), for example, assert that 11% of the value added GDP (gross domestic product) of a nation is attributed to CoPS[2]. But more importantly, CoPS have a significant impact on other product categories as well, because they form the underpinning of many commodity products[3] (Moody & Dodgson, 2006).

Since the seminal works of Miller et al. (1995) and Hobday (1998), the literature studying CoPS has focused on several themes, including the competencies and capabilities of CoPS firms (Bergek, Tell, Berggren, & Watson, 2008; Hardstone, 2004; Hobday, Davies, & Prencipe, 2005; Prencipe, 1997; Prencipe, 2000), inter-organizational collaboration and knowledge management within CoPS projects (Barlow, 2000; Brusoni & Prencipe, 2001; Chen, Tong, & Ngai, 2007; Marshall & Brady, 2001; Ngai, Chen, & Tong, 2008), the learning ability of project-based firms in successive CoPS projects (Barlow, 2000; Prencipe & Tell, 2001), the adoption and diffusion of CoPS (Baraldi, 2009; Inoue & Miyazaki, 2008), and innovations within CoPS projects (Magnusson & Johansson, 2008). There is, however, a shortage of literature focusing on industry change and in particular changes that are brought about by discontinuities in the CoPS context. Bergek et al.'s (2008) examination of the dynamics of change and shakeouts in the gas turbine industry, and Hardstone's (2004) study of the effects of CIM (computer integrated manufacturing) in offset lithographic printing and publishing, offer rare investigations of radical change in CoPS.

[2] Similarly, Acha et al (2004), report that the CoPS share of the United Kingdom GDP for manufacturing and construction was 19% at the end of the 1990s.

[3] CoPS are often machines that are used in high-volume production processes. Many modern services such as telecommunication and transportation rely on CoPS.

In this paper we aim to contribute to the literature by studying disruptive technological changes (Bower & C. M. Christensen, 1995; C. M. Christensen & Rosenbloom, 1995; C. M. Christensen & Bower, 1996; C. M. Christensen, 1997b) in CoPS industries. Although prior research has demonstrated the possibility of disruptive change in CoPS settings, such as in steel making and kidney disease treatment (Nair & Ahlstrom, 2003), the exact manner of disruption has not been explicated. Our objective is therefore to reveal the characteristics of disruptive change that are applicable for CoPS, which can at the same time provide firms positioned in CoPS industries important strategic indicators of disruptive change. To this end, we undertake a case study of a complex product system to observe the characteristics of disruptive change. While our case study cannot statistically verify the manner of disruption in CoPS settings, it nonetheless provides evidence towards a more comprehensive understanding of this phenomenon.

Our empirical study focuses on the Flash Converting technology, a CoPS innovation that is integrated into copper smelting facilities and used in one of the key processes that increase the purity of copper. Introduced into the copper production industry in 1995, the Flash Converting technology is emerging as a disruptive innovation as it displaces the incumbent Peirce-Smith converter, particularly in new green-field investments, by not only satisfying the customer's output performance requirements, but by also providing additional benefits such as significantly lowering emissions and improving total online availability (Kojo et al., 2009). Through semi-structured interviews with key respondents from the innovating firm, together with complementary secondary data, we assess the characteristics of disruptive change in this CoPS context by comparing our empirical observations with the traits of disruption established from a review of Christensen and his co-author's works that typically focus on commodity products.

The paper is organized as follows. We begin with a theoretical review of CoPS and disruptive innovations, and then synthesize these discussions by developing propositions connected with the characteristics of disruptive change in the CoPS context. Next, we describe our case study methodology, and in turn, discuss the case study results in light of our developed propositions. We conclude our paper with a discussion of the theoretical, managerial, and policy implications, as well as considerations for future research.

2. Theoretical Background

2.1 Complex product systems

The literature defines complex product systems (CoPS) as technological systems high in complexity and value, which are produced as customized, one-off or small batched capital goods items (Hobday, 1998; Miller et al., 1995). Examples of CoPS include:

- advanced CCGT (combined cycle gas turbine) power generating systems (Bergek et al., 2008)
- aircraft engines (Brusoni & Prencipe, 2001; Paoli & Prencipe, 1999; Prencipe, 1997)
- aircraft engine control systems (Prencipe, 2000)
- enterprise resource planning (ERP) systems (Baraldi, 2009)
- flight simulators (Miller et al., 1995)
- offset lithographic print and publishing technologies (Hardstone, 2004)
- offshore oil production platforms (Barlow, 2000; Teixeira, Guerra, & Ghirardi, 2006)

- satellites (Moody & Dodgson, 2006)
- telecommunication network management systems (Davies & Brady, 2000)
- water supply systems (Marshall & Brady, 2001)
- wind power systems (Inoue & Miyazaki, 2008)
- big science centers (Autio et al., 1996).

Scholars that have advanced the CoPS literature distinguish this product category from commodity products along a few key dimensions, including supplier-user relationships, product design characteristics, project durations, and innovation-paths. The resultant dichotomy is nevertheless a stylized view of product classifications and subsequently underscores certain limitations. Rather, the dimensions utilized to distinguish the two product categories can be seen as continuities along which a plethora of product types may lie. As a result, it may become difficult to identify the precise point of transition when a given CoPS becomes a commodity product with respect to the considered dimensions. Notwithstanding the inherent limitations posed by the stylized framework, we believe that the CoPS-commodity product dichotomy proposed by the literature, and which we employ in our present study, provides a fruitful starting point to enhance our understanding of the technological landscape by comparing and seeking patterns at the two ends of the continuum.

The notion of complexity that defines CoPS is born from the significant number of customized components and the vast array of knowledge that is necessary to produce these components and whole products (Hobday, 1998). For example, the production of modern aircraft necessitates a wide scope of knowledge in new materials, software technologies, fluid mechanics, and communications systems. Although CoPS are typically purchased by a single user, the vast knowledgebase needed to manufacture these products often exceeds the engineering capacity of a single firm, thereby necessitating their supply by a temporary project-based network of companies (Davies & Brady, 2000; Hobday, 1998; Miller et al., 1995). This network includes specialist suppliers, subcontractors, and system integrators, as well as overseeing organizations such as governmental and regulatory agencies (Hobday et al., 2005). Thus, while some commodity products (e.g. personal computers and smartphones) display complexity in their technical design, the complexity inherent in CoPS is seen by scholars to extend beyond the technological to the project initiative and its management that brings about a more customized end product.

Most importantly, CoPS are deemed to form a generic category of industrial products, which display product and market characteristics that distinguish them from commodity products, such as cars, semiconductors, and consumer electronics (Hobday, 1998). Firstly, CoPS are capital goods that are acquired through business-to-business (B2B) transactions and have higher unit costs than commodity products, which are often mass-produced and devised for downstream consumption via business-to-consumer (B2C) transactions (Hobday, 1998). The transactions in CoPS markets tend to be few in number although large in magnitude, while commodity product markets are signified by a large number of transactions with many buyers and sellers. Secondly, the components of CoPS are typically tailor-made to suit the buyer’s requirements, whereas commodity products generally consist of standardized or modular components[4]. The potential for modular innovations (Henderson & Clark, 1990) in CoPS is therefore likely to be lower than for commodity products, although modularization and standardization can take place in CoPS over time (for example aircraft engines, see Brusoni & Prencipe, 2001), concurrently countering inherent complexity[5]. Thirdly, CoPS are likely to demonstrate complex component interfaces within a hierarchical system structure (Shibata, 2009), in contrast to commodity products, which tend toward simpler interfaces and a simpler architectural structure. A greater potential therefore exists for architectural innovations (Henderson & Clark, 1990) in commodity products than in CoPS. And fourthly, the life cycle of commodity products is shorter than CoPS, which can span several decades.

The evolution of commodity products and their related industries are often traced through life cycles stretching from birth to maturity (Abernathy & Utterback, 1978; Bayus, 1994; Day, 1981; Dhalla & Yuspeh, 1976; Levitt, 1965). This life cycle is brought to an end by punctuated equilibria as firms exploit technical opportunities to introduce radical changes in products (Anderson & Tushman, 1990; Schumpeter, 1968; Tushman & Anderson, 1986). The subsequent emergence of a dominant design, in turn, signals industry shakeout and redefines industry structure (Anderson & Tushman, 1990; Tushman & Anderson, 1986). The nature of CoPS industries, by contrast, tend to be characterized by temporary multi-firm alliances that are formally established to coordinate innovation. The elaborate network of companies is formed for the purpose of each CoPS project rather than subsequent to radical product innovations.

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[4] According to Ulrich (1995), there is a one-to-one mapping between physical components and functional elements in a modular architecture. This additionally entails that the interfaces between modules are decoupled (Sanchez & Mahoney, 1996; Ulrich, 1995).

[5] CoPS can also transform over time into mass produced capital goods or consumer goods (Acha et al., 2004).

Furthermore, this network is often disbanded at the completion of a CoPS project, which can impair the inheritance of acquired technological capabilities for successive projects (Hobday, 1998; Prencipe & Tell, 2001)[6]. As a result, CoPS typically do not reach the later stages of a life cycle denoted by volume production and incremental process innovations as observed in traditional models (Miller et al., 1995)[7].

The innovation process in CoPS is driven by producer-user interaction. The continuous dialogue between the supplier and the user is often necessary because the user redefines product requirements throughout the project, demanding higher performance, capacity, and reliability, while at the same time adding further complexity to the coordination of the project. Users can additionally shape innovation paths in CoPS through their direct role in funding R&D (research and development). Altogether, user involvement in product design and R&D creates demand driven innovation, or innovation through "user-push", as witnessed in the development of passenger aircraft and telecommunication exchanges (Hobday, 1998). This is in contrast to innovation studies pertaining to stand-alone, commodity products, which distinguish firms and markets as distinct entities, and propose that firms compete in a technology race while users decide on successful product designs among emerging alternatives (Adner, 2004; Anderson & Tushman, 1990; C. M. Christensen, 1997a; Moore, 1999; Mowery & Rosenberg, 1979). Hence,

[6] Notwithstanding, Davies and Brady (2000) have shown that firms taking part in CoPS projects attempt to gain economic benefits through the repetition of similar project types. This is illustrated in CoPS such as nuclear power plants that are characterized by successive generations.

[7] Although CoPS represent low volume, custom made products, these projects can last for a very long time, potentially spanning decades, such that longer-term relationships materialize between firms in the CoPS network of producers, users, and regulatory bodies involved in a particular project (Hardstone, 2004).

innovation of commodity products is viewed to be supplier driven while market selection mediates this innovation path.

Some CoPS, such as military systems, additionally engage the intervention of governments, standards bodies, and regulatory bodies, as these actors are stakeholders of the project and its outcomes. The ensuing dialogue between the network of CoPS companies and these regulators can shape innovation paths by dictating matters such as safety issues, as well as interfacing standards among different CoPS that come together to form large technical systems (Hughes, 1983; Mayntz & Hughes, 1988), such as railway networks or airports (Hobday, 1998; Miller et al., 1995).

2.2 Disruptive changes in CoPS

Technological discontinuities at the industry level can be delineated into two primary categories. Discontinuities that maintain performance improvement along the existing trajectory of development despite their modular, architectural or radical (Henderson & Clark, 1990) nature are referred to as 'sustaining' technological changes. By contrast, 'disruptive' technological changes are discontinuities that cause paradigm shifts (Dosi, 1982) and establish new trajectories of technological improvement which carry the potential to overthrow established firms (Bower & C. M. Christensen, 1995; C. M. Christensen & Rosenbloom, 1995; C. M. Christensen & Bower, 1996; C. M. Christensen, 1997b). Disruptive innovations begin substituting for incumbent technologies by satisfying the mainstream market's existing performance demands and simultaneously offering a new set of values. As a result, these innovations disrupt markets by changing the rank-ordering of the criteria by which customers choose one product or service over another – in other words, disruptiveness is a market-based process (Govindarajan & Kopalle, 2006). 'Nanotechnology' presents a prominent example of a relatively recent general purpose technology that is anticipated to cause disruptive changes in a variety of industries, including materials, automotive, aerospace, electronic production, and healthcare (Shea, 2005)[8].

To understand the nature of disruptive change, we deemed it appropriate to review the works of Christensen[9] who has coined the concept and also provided illustrations of disruptive innovations in the context of a wide range of products and industries. We present a list of these disruptive innovations from our review in Table 1.

Insert Table 1 about here

Our review of the disruptive innovations listed in Table 1 reveals a set of repeating characteristics that mark each disruption[10]:

[8] To illustrate this further, Shea (2005) suggests that the firm General Electric (GE) has commenced work on particular product categories, the outcomes of which could lead to disruption. GE's nanoscience efforts include the use of nanotubes in CT scanners, nanoceramic coating applied to hydroturbines, and the use of nanoparticles to improve molecular imaging.

[9] We have produced this table from the review of published journal articles authored or co-authored by Christensen, conducted using the ISI Web of Knowledge at the end of 2011.

[10] The characteristics of disruptive change that emerge from our review also align with the characteristics established by Govindarajan and Kopalle (2006), as well as by Yu and Hang (2010).

(a) the incumbent technology overshoots the performance demanded by mainstream customers, thus creating a vacuum for new technologies to enter and challenge for the same market

(b) disruptive innovations are nurtured in nascent or emergent markets which appreciate value attributes that are not central to competition in mainstream markets

(c) disruptive innovations initially lack the technological performance levels that are required to penetrate mainstream markets

(d) disruptive innovations typically have lower sticker price per unit than mainstream products even though their cost in use is higher

Christensen advocates these characteristics to serve as harbingers of technological change that can cause upheaval of industry structure, and therefore form a set of notable indicators that firms are encouraged to assess over time. Interestingly, we observe that the disruptive technologies listed in Table 1 can generally be classified as commodity products and services, with only a few illustrating disruptive change in CoPS contexts[11]. In other words, these disruptive innovations are predominantly B2C products with a high number of market transactions and large number of buyers and sellers, and which are mass-produced with

[11] Energy production (Hart & Christensen, 2002), semiconductor production (Hart & Christensen, 2002), steel production (C. M. Christensen, 1997a), and textile production (C. M. Christensen & Bower, 1996) can be analyzed through a CoPS lens, although Christensen's depiction of these disruptive changes pertain to production methods as opposed to specific complex product systems.

standardized components. Because of this general tendency, the major proposition we raise in our paper is that the emergent characteristics of disruptive innovation are relevant for commodity products but may not necessarily present the characteristics of disruption in CoPS settings. The managerial implications derived for firms competing in commodity product industries may therefore also be inapplicable for firms competing in CoPS industries. We elaborate on the underlying reasons of our general proposition below.

Firstly, there is an apparent decoupling between technology suppliers and the adopter markets for commodity products. This detachment catalyzes the manifestation of disruptive change as suppliers can overshoot the performance requirement of customers and create a void which can be filled by a technological innovation exogenous to the mainstream market. Moreover, the disruptive technology often succeeds by causing a low-end disruption (i.e. by initially penetrating the low-end of the market's performance spectrum), and having time to acquire demand gradually over time (Adner, 2004). By contrast, the connection between technology suppliers and adopters is tightly knit in CoPS. Innovation paths in CoPS are guided by a dialogue between the producing companies and users, as well as overseeing bodies (e.g. the government, regulatory and institutional entities)[12]. Users and regulators can therefore motivate but can also hinder the adoption of new CoPS innovations (e.g. safety requirements related to civil aircraft engine industry). Hence, we posit that there is limited scope for suppliers to develop superfluous technologies that encourage the penetration of disruptive technologies

[12] For example, engine makers in the aircraft engine industry have to comply with the regulations specified by certification authorities, such as the FAA (Federal Aviation Administration) in the USA, and EJAA (European Joint Airworthiness Authorities) in Europe (Brusoni & Prencipe, 2001).

into the CoPS market, and that the success of CoPS projects is less likely to depend on low-end penetration than in commodity markets.

Proposition 1: *The tight connection between suppliers, adopters, and regulators reduces the likelihood of disruptive innovations resulting from incumbents overshooting customer demands in CoPS industries.*

Secondly, the high-volume production and the high number of market transactions that characterize commodity products signal the co-existence of different market segments and market niches. Organizations therefore have the capacity to develop their technologies toward applications valued in targeted niches external to the mainstream market, thereby creating disruptive potential in accordance with the established model of disruptive change. In comparison, the supply side of CoPS is marked by low volume production, while the demand side is marked by a low number of market transactions. System integrators as well as specialized companies find it additionally difficult to diversify to other CoPS industries and markets where new innovations can be incubated. This rigidity is bestowed by the investments in the skills and assets that have been tailored to meet current business needs, and which are of little value outside of these business arenas. Such production characteristics subsequently suggest that niche markets are less likely to exist in CoPS contexts and therefore less likely to nurture disruptive innovations.

Proposition 2: *The production characteristics of CoPS industries reduce the likelihood that disruptive innovations are nurtured in niche markets.*

Thirdly, disruptive technological changes are exogenous to a given value network. This appears to be a necessary condition because the new innovation that carries disruptive potential cannot gain a foothold in the mainstream market due to performance deficiency, and is compelled to access a separate market niche at the outset. The capacity of a technology nurtured in a foreign value network to supplant a functionally similar technology in a focal value network, indicates that these value networks are likely to be nested, hierarchical structures, comprising technological modules rather than mere sub-systems. Technological modules are interchangeable between value networks and this allows disruptions to materialize. Although CoPS display a hierarchical network of technologies (and organizations that produce them), these technologies are customized, and are often absent of standardization and modularization, with complex sub-system interfaces. As a result, technological sub-systems cannot be readily interchanged between different CoPS networks. The absence of readily accessible market niches additionally means that potentially disruptive innovations in CoPS contexts need to engage in competition with the incumbent technology at the outset, rendering performance deficient innovations less likely to survive this competition. We subsequently anticipate a lower likelihood of successful disruptive CoPS innovations that initially lack the performance levels required to penetrate mainstream markets.

Proposition 3: *The absence of niche markets reduces the likelihood that disruptive CoPS innovations lack the performance levels required to penetrate mainstream markets at the outset.*

And fourthly, disruptive technologies in commodity product industries are often based on simpler architectures and therefore boast lower prices, thus allowing new innovations to cause low-end disruptions according to the established model of disruptive change. By contrast, CoPS innovations display a greater propensity for more complex architectures than their predecessors due to the addition of sub-systems that increase performance or provide additional functional features demanded by the customer. We therefore suggest that the acquisition cost of a disruptive CoPS innovation is also likely to be higher than the incumbent CoPS technology.

Proposition 4: *The inherent complexity of disruptive CoPS innovations is likely to result in higher sticker prices.*

Collectively, the above stipulated four propositions are built on the differences in innovation dynamics, competition, and industry structure between CoPS and mass-production industries. Frameworks that are relevant for commodity products may therefore not be relevant for CoPS (Hardstone, 2004; Hobday, 1998). For this reason, we suggest that disruptive changes in CoPS industries may display a different set of characteristics than those observed for traditionally examined commodity products. Next, we intend to present evidence of this major proposition in the context of a particular case, and to underline the emergent characteristics of disruptive change that are applicable in CoPS settings.

3. Methodology

The research question we pose in this paper is; "how do disruptive technological changes take place with respect to the industrial product category of CoPS?" To answer this question, we employ the case study methodology in our empirical work, as our objective is to investigate the disruptive innovation phenomenon in a contemporary CoPS example. Furthermore, the case study is a preferred empirical approach for the form of research question that we have raised (Yin, 1994), through which we intend to understand the process and characteristics of disruptive change in a systemic context. Following the general outline stipulated by Yin (1994), we examined the four propositions that we have derived from theoretical investigations pertaining to disruptive technological changes in CoPS. To this end we implemented a single, holistic case study design (Yin, 1994), and collected and analyzed data through different case related sources. These results were then used to develop a case report, which also provided theoretical and managerial implications.

In accordance with our research question, the CoPS technology was chosen as the unit of analysis. Specifically, we selected 'Flash Converting' as the technology, which we deemed was representative of a disruptive innovation in the CoPS context, and investigated the technological changes that related to this innovation from the time of its first implementation in the copper production industry (i.e. 1995) until the present. We used multiple sources of evidence in our study, which concurrently increased the construct validity[13] of our findings. The evidence accessed in our case study was sourced from two separate interviews conducted with two key informants, and supplemented by documents such as books and published scientific articles, especially in the engineering literature.

The interviews were kept open-ended, with a focus on guiding the conversation rather than maintaining a strict query structure. This allowed the respondents to freely provide their opinions and information concerning the case. The duration of each interview was approximately three hours, with some flexibility implemented to cater for the open-ended nature of the interview. Our respondents were key informants, who had been long-term employees of the firm Outotec[14], which had developed the disruptive Flash Converting technology, and who had participated in the project from the beginning and seen this technology through to its first implementations. These interviewees were high level managers who not only possessed an overview of the project but were also informed of its technical aspects. At the same time, interviewing experts at Outotec afforded us access to knowledge of the copper extraction process, copper converting technologies, and the networks of organizations involved in the CoPS in question, from the point of view of the company causing the disruptive change.

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[13] Here, we borrow Yin's (1994) definition of construct validity, which concerns "establishing correct operational measures for the concepts being studied" where "the chosen parameter must be justified". The construct validity of our case study was further strengthened through the open-ended interview format, triangulation of data sources, and by using Christensen's theoretical framework directly, where the indicators of disruptive change have been established through multiple case studies.

[14] Outotec (formerly Outokumpu Technology Oy) is a global engineering company with its headquarters in Finland. It develops and provides technological solutions for the minerals and metals processing industry.

Multiple investigators were used to collect data during the interviews. One investigator was assigned the role of producing an audio recording and making hand-written notes, while a second investigator undertook the role of questioner and making informal observations. The audio recordings were systematically transcribed by an external analyst, and the transcript records were scoured by the investigators in a systematic fashion to reveal vital information. This information was, in turn, compared with the notes and observations produced during the interviews. In this manner, we performed triangulation among different evaluators (Yin, 1994).

To analyze the attained data we performed pattern matching (Yin, 1994), and compared the empirical based pattern with our predictions derived from theory. In this manner, we looked for patterns between our case study findings and the multiple dependent variables derived from our major proposition that disruptive change in CoPS settings will not follow the general trend observed for commodity products. We aimed to evaluate this major proposition by reviewing the four specific propositions that were derived theoretically.

4. Case Analysis: The Flash Converting technology

Flash converting is one of a series of several processes that help extract copper from its ore. These processes are displayed in Table 2, along with their outputs which are carried onto adjacent processes in the chain, as well as the obtained pure copper ratio which increases from one process to the next.

Insert Table 2 about here

Copper extraction begins with the mining of copper ore, which is performed in various locations around the world. The largest copper mining operations as of 2009 are in Chile, The United States, Peru, and Australia[15]. The mined ore, however, contains only a very small percentage of copper material (below 0.6%), and must therefore undergo several processes to separate it from the rock and other valueless materials that surround it. The next step in copper extraction is comminution, which reduces the mined solid materials in size, for example through crushing. Froth flotation, in turn, processes the crushed ore to produce copper concentrate with a ratio of approximately 30% copper. Traditionally, the copper concentrate was transferred to the intermediary roasting process, whereby the concentrate has been partially oxidized for further treatment. However, in recent decades the adoption of the flash smelting technology has made this step redundant.

Flash smelting is a high temperature process that produces liquid in the form of copper matte and slag (unwanted metal and silicon oxides). Within this process, the slag is separated from the copper matte and reprocessed to recover remaining copper. The copper matte, containing preferably around 60-70% copper in the form of copper sulfides, is instead transferred to a flash converting process, which removes the sulfur as sulfur dioxide (SO_2). The copper that is attained after the converting process is 98% pure, and because of the broken surface that is visible, is referred to as blister copper. Any remaining oxygen in the copper is

[15] http://www.indexmundi.com/en/commodities/minerals/copper/copper_t20.html

finally removed in the reduction phase that employs an anode furnace, and later in a refining procedure (electrolysis) (Schlesinger et al., 2011).

4.1 Flash Converting as CoPS

The actors which comprise the copper production supply chain include mining companies, smelters, and refiners, or alternatively a vertically integrated smelter-refiner company, and a vast number of equipment suppliers (Schlesinger et al., 2011). Along this chain our study focuses on the smelting process, where copper smelter firms bring together a number of CoPS, including Flash Smelting Furnaces, Flash Converting Furnaces, steam dryers, and anode furnaces, within a single production facility. Although a distinct CoPS on its own, the Flash Converting technology is at the same time a sub-system of the larger copper smelting facility[16]. The Flash Converting technology is provided by Outotec, which acts as the system integrator and coordinator of the Flash Converting CoPS project[17]. It supplies the core, proprietary technologies of Flash Converting, while integrating technologies provided by a number of suppliers (with Outotec among them) including the feeding system, and Outotec's matte burning, furnace structure and cooling, and tapping sub-systems.

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[16] In our hierarchical view of the technological system we follow Christensen's illustrations, such as that for the hard disc drive, which was the unit of analysis for disruptive change and a sub-system within the holistic computer system.

[17] Mitsubishi has been Outotec's largest competitor, having developed a similar concept to Outotec's Flash Converting technology in 1990 but quit manufacturing this rival technology in 2000, apparently because this line of business was deemed not significant enough within the corporation. Other competitors include Norand (exited the industry), Ausmelt (acquired by Outotec), and Isasmelt.

We classify the Flash Converting as a CoPS based on several product characteristics. First, Flash Converting is inherently complex, requiring knowledge from a wide range of scientific realms, including "flash reactions, slag chemistry, flow phenomena in the furnace, and the process thermodynamics" (Kojo et al., 2009). This characteristic requires the involvement of a number of actors such as component suppliers, universities, and research laboratories[18], in addition to the manufacturer of the flash converter itself. Second, the Flash Converting technology is a low unit volume, B2B product that has high unit cost, and belongs to markets marked by a low number of transactions[19]. In such markets, the cost and complexity associated with product acquisition leads to a substantial amount of interaction between the user (i.e. the copper smelter) and the supplier in order to deliver a product that satisfies operational requirements. For instance, the copper smelter, namely Kennecott Utah Copper (Salt Lake City, Utah, USA), worked together with Outotec from initial concept development to the pilot testing of the flash converting process, leading up to and including its first commercial application. Third, there is salient involvement of regulators (especially setting of environmental emission standards and granting or denying permissions for building and operating smelters) in the development of the flash converting process, which guides the path of innovations in converting techniques. And finally, flash converters have a long life cycle, spanning decades.

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[18] The development of the flash converting technique involved the Helsinki University of Technology, University of Utah, and Columbia University in the City of New York, together with Outotec's own research facilities.

[19] According to United States Government records, there were more than 150 copper smelters in operation around the world in the early 2000s (http://mrdata.usgs.gov/copper/), which provides an approximation of the potential market size for Flash Converting. Furthermore, our interviews revealed that the erection of a copper smelting plant, which implements Flash Converting, can cost hundreds of millions of Dollars, illustrating the magnitude of costs incurred in the industry.

4.2 Flash Converting as a disruptive technology

The dominant copper converting technique over the past 100 years has been the Peirce-Smith converting process (Kojo et al., 2009). Even today, over 90% of the world's copper matte converting output is generated through the Peirce-Smith process (Schlesinger et al., 2011). However, this incumbent CoPS, itself a sub-system of the larger copper smelting facility, is currently facing competition from the Flash Converting furnace, the disruptive CoPS innovation that forms the focus of our case study. Flash converting, as an alternative technique, was first presented as a concept in 1983, and the first converter went into commercial production in 1995 at Kennecott in Utah, USA (Kojo et al., 2009)[20]. Since then four other installations have been made[21]. Flash Converting has emerged as a disruptive technology, especially for green-field investments, because it not only satisfies the production capacity and yield requirements of mainstream customers, but also offers additional value to copper smelters on other dimensions. This CoPS innovation therefore fits the market-based view of disruptiveness (Govindarajan & Kopalle, 2006) by altering the rank-ordering of the product attributes valued by the customer. Some of the advantages of flash converting in comparison to the Peirce-Smith converting technology include (Kojo et al., 2009):

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[20] According to Schlesinger et al. (2011), Flash Converting is one of six alternative techniques to the incumbent Peirce-Smith converter. Other techniques include the Hoboken converter, Noranda continuous converting, the Mitsubishi top-blown converter, Ausmelt TSL (top submerged lance) batch converting, and Isasmelt TSL batch converting of which none has gained a similar market position as flash converting.

[21] http://www.outotec.com/en/About-us/Our-technologies/Smelting/Flash-smelting-Flash-converting/#tabid-5

- fewer SO_2 emissions (the SO_2 concentration in the off-gas stream increases from approximately 10% in the Peirce-Smith converting process to approximately 62% in the flash converting process, thus accounting for the capture of a greater amount of harmful gas emissions)[22]
- improved total online availability and longer campaign life (the availability time increases from approximately 42% in the Peirce-Smith converting process to approximately 92% in the flash converting process due to reduced number of shutdowns and reduced frequency of relinings of the furnace unit – from once per year to once per five years, at least)
- easier use of continuous process (enabled by constant feed material quality, whereby more homogenous matte, with respect to copper content, is delivered to the furnace)
- reduced energy consumption (approximately 20% lower than in the Peirce-Smith converting process)
- reduced disruptions in production through decoupling of process stages (in the Peirce-Smith converting processes are coupled).

The Flash Converting technology has begun to supplant the Peirce-Smith converter in copper smelting facilities as customers have become aware of these additional benefits delivered by this new technology. In order to reveal the disruptive change characteristics that

[22] Flash Converting has advantages pertaining to other environmental indicators as well, including copper recovery and specific heavy metal discharges to water (Kojo, Lahtinen, & Miettinen, 2009).

are relevant for this CoPS, we appraise the four traits of disruptive change that emerge from a review of Christensen's works.

4.2.1 Incumbent technology overshoots mainstream market performance demand

The performance metric that has been central for the copper converting industry is that which has historically guided the technological trajectory of the copper converting process using the Peirce-Smith method, and at the same time used to assess the viability of new technologies in copper converting such as flash converting. Some of the parameters important for copper smelter operators include operation costs, profit to total income ratio, and pre-tax operating profit versus capital employed (Kojo et al., 2009). Moreover, according to our interviewees, additional key considerations are the sheer production capacity (usually expressed in metric tons per year) that is obtainable, and the upfront capital expenditure required for capacity addition or green-field investment. Taking into account the multifunctional aspect of CoPS, the multiplicity of important performance parameters related to flash converting technology is not surprising. Our interviewees subsequently did not immediately lead us to a distinct technical parameter in the industry that would allow examination of this first characteristic of disruption. Nevertheless, we established a relatively more central parameter that had been locked-in (Cowan & Hultén, 1996; David, 1985) to guide the development trajectory of the Peirce-Smith converting technique to be 'process capacity' from the remarks of one interviewee:

> "The Peirce-Smith converter has become the dominant technology because it was the only option for a long time, and so much investment has been made in these

converters. The Peirce-Smith system includes several units so producers can increase capacity in a modular way by purchasing additional units."

Following the traditional disruption model, we would expect the incumbent converting technology to overshoot the process capacity requirement of copper smelters over time. Consequently, smelters would be willing to integrate alternative converting technologies into their facilities as long as their capacity requirements would be met. In the flash converting case, however, we observed that the capacity performance of the Peirce-Smith process did not exceed that demanded by the customers when Flash Converting disrupted the industry. Rather, as one respondent commented, processing capacity could be flexibly adjusted to meet the requirements of the smelting facility with the Peirce-Smith converter:

"The Peirce-Smith converter system includes several parallel converter units so that its capacity can be increased by adding more Peirce-Smith units."

This finding is commensurate with our first proposition that anticipates the absence of superfluous technological performance, which would act as a precursor to a disruptive CoPS innovation. The flash converting case does not therefore align with the traditional model of disruptive technological change, whereby surplus incumbent performance creates an opportunity for new entrants to target the lower echelons of the mainstream market with their innovations. Rather, the potential for disruptive change in this CoPS context is born from the changes in the regulatory environment:

> "Environmental pressures have increased in many countries and tightened legislation and forced producers to adopt more environmentally friendly solutions. If the old technology is replaced by flash converting, emissions would decrease significantly. Many countries have serious problems with emissions and flash converting would offer clear improvement for their situation."

This underscores the role of external agents as well as factors that guide innovation paths in CoPS settings. Our case study also suggests that while there is an absence of technological performance surplus, the disruptive CoPS innovation competes with the incumbent technology by providing additional benefits, as also observed in the traditional model of disruptive change.

4.2.2 *Disruptive innovation is nurtured in nascent or emergent markets*

In our case analysis, we find evidence that the Flash Converting technology was able to enter the mainstream market, having satisfied the existing performance demands of copper smelters, and concurrently offer additional value to these customers:

> "Flash converting had several advantages compared to Peirce-Smith so there was no need to find nascent or emergent markets when flash converting was developed."

While this finding is in support of our second proposal that niche markets are less likely to exist in CoPS contexts and therefore less likely to nurture disruptive innovations, it simultaneously highlights the importance of defining niche markets in the analysis of disruptive change. In the established model of disruption, market niches are often portrayed as alternative product application arenas (e.g. laptop computers offered a niche market for smaller hard disc drives when desktop personal computers formed the mainstream market). In analyzing the disruptive potential of CoPS, however, additional dimensions of market niches may need to be taken into account. In the B2B context, suitable market segments for a new CoPS innovation can be determined through geographics and firmographics (or business demographics), which refer to approaches used in industrial segmentation along dimensions such as geographic location (as regional differences can influence purchasing behavior), number of years a firm has been in business, and the size of buying firms. There are two firmographic segmentation variables that pertain particularly to the Flash Converting case. The first one is the differentiation between brown-field (i.e. already existing copper smelter facilities) and green-field (i.e. new or planned smelters). Of these, green-field projects are more receptive towards the new technology, due to the lack of prior investments in the Peirce-Smith converters. The second segmentation criterion is the stringency of environmental regulations under which the firm (or the focal smelter) operates, because strict environmental criteria are exceedingly difficult if not impossible to meet with the old Peirce-Smith process. For this reason, Flash Converting has gained an initial foothold in the USA (Kojo et al., 2009) prior to entering other geographic regions such as the large market of China.

Nonetheless, according to our interviewees, Flash Converting did require nurturing in order to make it technologically ready and commercially credible. The joint development effort with a pilot customer, who became the first copper smelter to commercially integrate the technology into its smelting process in 1995, was vital. This, in turn, served as a crucial reference case for subsequent adopters who, as a general rule, are exceedingly cautious to invest up to hundreds of millions of Dollars in a facility unless all its key technologies are known to perform as required[23]. In any event, the initial customers were mainstream copper smelters with conventional production requirements, with an added emphasis on environmental performance.

4.2.3 *Disruptive innovation initially lacks mainstream market performance demand*

In the traditional model of disruptive change, a new technological innovation fails to gain mainstream market preference because it does not fulfill the customer demand with respect to the central performance parameter. This new innovation therefore causes a low-end disruption by initially satisfying lower performance demanding customers, and later moves progressively up-market with increasing performance. However, our case study shows that the process capacity performance of flash converting satisfied the requirements of the copper smelters from the outset[24], and therefore did not demonstrate low-end disruption:

[23] The metal market situation has a big influence as well. Approaching the 21st century, the metal market improved and metal prices increased, thus there was a growing demand for new smelters.

[24] According to Schlesinger et al. (2011), the flash converter installed at the Kennecott facilities produces approximately 1300 tonnes of blister copper per day, which is roughly the output of three large Peirce-Smith converters.

> "The unit capacity of flash converting is larger than Peirce-Smith's capacity. This is emphasized when a green-field plant is built. Capacity of one flash converter is high enough even for the biggest green-field plants. Capacity of one Pierce-Smith unit is much lower but total capacity of the Pierce-Smith plant can be increased by building several Pierce-Smith converters."

This finding supports our third proposition that the absence of readily accessible market niches renders successful disruptive CoPS innovations to initially meet the performance levels required to penetrate mainstream markets. In fact, the comment of the respondent indicates that the Flash Converting technology not only satisfied customer requirements, but exceeded these demands. We subsequently deem Flash Converting to represent a high-end disruptive change (Govindarajan & Kopalle, 2006), where the performance of the new innovation supersedes that of the incumbent when first introduced to the market.

4.2.4 Disruptive innovations have a lower unit price

The traditional model of disruptive change underlines that disruptive technologies typically have a lower unit price, despite having a higher usage cost. Our study reveals contrary evidence in the case of the Flash Converting technology. As one respondent stated, higher unit costs are incurred due in particular to the larger unit size of the converting furnaces. Furthermore, the operating costs of the copper smelter are reduced through the integration of

Flash Converting, bestowed by their process related advantages such as availability, campaign life, and process continuity:

> "The investment cost of a flash converting unit is higher than the Peirce-Smith unit because the unit size and capacity of flash converting is much larger. Operating costs of flash converting are much lower than the Peirce-Smith, especially for a high capacity plant."[25]

This finding provides evidence for our fourth proposition that the price tag of disruptive CoPS innovations are likely to be higher due to the greater complexity in the architectural design of these product systems in comparison to their predecessors. Taking into account the life cycle of commodity products that emphasizes increasing price competition over time, we expect lower unit costs to characterize disruptive commodity products. However, our investigation shows that these economic trends may not materialize with respect to CoPS, due in particular to the customized and more complex nature of these technologies, which restricts the attainment of higher volume production that can lead to cost reductions.

Collectively, our results show that the two types of disruption identified by Christensen and Raynor (2003), namely, low-end disruption and new market disruption processes do not hold in our case study of the Flash Converting technology. While the type of disruptive change witnessed in this case is comparable to the low-end disruption process, whereby a new technology enters competition with the incumbent technology for the same customer segment,

[25] Operational costs are estimated to be approximately 20% lower than the Peirce-Smith process.

the four characteristics that define this process are not supported in our case evaluation. New market disruption by comparison entails the introduction of a new innovation that addresses non-consumption rather than existing consumer groups. Moreover, new market disruptions are likely be caused by simpler, more affordable innovations that create a need in the customers, motivating them to move from the traditional mainstream market to the new one generated by the new innovation. Our results indicate firstly that the Flash Converting technology enters competition with the Peirce-Smith converter for implementation into the facilities of the same copper smelters (who represent the adopting market), as observed in the pioneering case of Kennecott in Utah as well as cases that have followed[26]. Secondly, for the mode of new market disruption to be relevant in this case, we would anticipate the Flash Converting technology to be adopted by a new group of customers that had previously not been able to utilize the Peirce-Smith converter (i.e. non-consumers), despite being in the copper smelting business. Although green field projects carry this potential, our interview results suggest that these are totally new endeavors that require a decision to adopt either the incumbent or the new innovation. And thirdly, the Flash Converting technology is neither simpler nor more affordable than the incumbent Peirce-Smith converter, which further refutes the new market disruption process.

[26] A review of furnace installations documented by the US Government and Outotec over the past decade reveal that with one exception, all of the companies that have acquired the Flash Converter have operated copper smelting facilities previously, thus indicating that they have been active in the copper industry even if the sites themselves may be classified as greenfield investments.

http://pubs.usgs.gov/of/2003/of03-075/CSTable.xls

http://www.outotec.com/en/About-us/Our-technologies/Smelting/Flash-smelting-Flash-converting/#tabid-5

5. Discussion and Conclusions

In this paper we aimed to contribute to the literature studying industry level changes in CoPS (complex product systems) contexts, specifically focusing on disruptive technological changes in CoPS industries. The objective of our paper was to derive a set of strategic implications for firms positioned in these industries by revealing the traits of disruptive change in CoPS settings, in contrast to those identified for traditionally analyzed commodity products. To this end, we developed theoretical arguments to justify our anticipation of a different set of disruption characteristics to materialize in the CoPS environment, and in turn, sought empirical evidence of our theoretical grounding through a case analysis. We studied the Flash Converting technology, a CoPS employed in copper production, comparing the characteristics of disruptive change in this CoPS context with the traits of disruption traditionally established for commodity products, such as cars, semiconductors, and consumer electronics.

The case study provided evidence for our theoretically derived propositions that disruptive changes in CoPS industries tend to be marked by the following characteristics:

(a) the incumbent CoPS technology does not overshoot mainstream market performance demand
(b) the disruptive CoPS innovation is not nurtured in low-end niche markets
(c) the disruptive CoPS innovation initially satisfies mainstream market performance demand
(d) the disruptive CoPS innovation has a higher unit price than the incumbent technology.

Together, these observations supported our major proposition that disruptive changes in CoPS settings do not demonstrate the traditional logic of disruption established for commodity products, and that the strategic considerations for both incumbent and innovating (i.e. the supplier of disruptive innovation) firms in CoPS industries will subsequently differ from those relevant for commodity product industries. We elaborate on the resulting managerial and policy implications below.

The first difference we have observed is that disruptive changes in CoPS do not result from asymmetries in the technological landscape caused by superfluous performance supply. Hence, firms positioned in CoPS industries cannot implement an offensive or defensive strategy premised on a growing void between customer demand and performance supply, as in commodity markets. Rather, an important and salient characteristic that needs to be considered when assessing disruptive change in CoPS, more so than in commodity products, appears to be the role of overseeing bodies, such as governments, and regulatory and institutional entities. Regulators can cause barriers to innovation, but they can also motivate disruptive change. For instance, our case study showed that burgeoning environmental and regulatory pressures on copper smelting firms to control the amounts of effluent gases, such as SO_2 (Kojo et al., 2009), have led to concerns over the incumbent Peirce-Smith converter technology, and concurrently created a window of opportunity for alternative technologies to enter the milieu. This finding also aligns with Nair and Ahlstrom's (2003) work on kidney disease treatment, which similarly illustrated the role of regulations in determining the innovation path of CoPS in the medical field.

Policy makers are subsequently in a position to determine the path of new, disruptive innovations. Constituting the superstructure about the CoPS innovation, regulators may not only intervene indirectly through the creation of technological asymmetries (e.g. establishing new performance criteria), but also directly by providing subsidies to alleviate the financial burden of innovation (or by contrast, introducing penalties to curb undesirable development) and by engaging external knowledge providers such as Universities to accelerate the innovation process. Furthermore, policy makers can intentionally create technological niches where new CoPS innovations can be nurtured, such as markets for military applications.

We secondly observed that while the disruptive technology for commodity products is typically protected in an initial application niche, such niches are less likely to exist to harbor a new innovation in the CoPS context, and the disruptive CoPS technology is therefore more likely to enter the mainstream application arena at the time of initial commercialization. Moreover, as Nair and Ahlsrom (2003) have also shown, the co-existence of competing technologies in CoPS industries such as in steel making is common and can persist for a long duration of time, thus supporting our own empirical findings. For incumbent firms, this characteristic reduces the difficulty of identifying potentially disruptive innovations, a dilemma which is highlighted in many of Christensen’s case illustrations. The ensuing competition is subsequently reminiscent of more traditional rivalry posed by new entrants or substitute providers, and should compel incumbents to engage in competitive strategies such as product differentiation or cost reduction (especially given that disrupting CoPS innovations are likely to have a higher price tag).

Our third observation was that the disrupting CoPS innovation satisfies and possibly even exceeds the performance demand of the mainstream market when first commercialized. This condition is connected with the lack of protective niches, such that the innovation is compelled to deliver the customer required performance when entering the competitive fray. As a consequence, the CoPS innovation follows a high-end disruption pattern (Govindarajan & Kopalle, 2006; Yu & Hang, 2010) rather than the traditional low-end disruptions noted for commodity products. Our case study also suggested that the disrupting firm attains a competitive position when it can offer additional value attributes through its innovation, a mechanism of disruption also witnessed in commodity product industries. The competitiveness of the disrupting firm is further strengthened by the specialization of skills and assets that instill rigidity in incumbent firms, thereby limiting their capacity to thwart the threat of the new innovation. Moreover, unlike for commodity products where codified knowledge may be readily copied, it is difficult for incumbents in the CoPS industry to reverse engineer and access crucial knowledge required for replicating the new CoPS innovation even in the absence of patent protection.

Notwithstanding these advantages, the innovating firm must overcome some hurdles to disrupt the incumbent CoPS industry. The absence of product application niches, for instance, means that the innovating firm has less time to establish a competitive value proposition. Under these circumstances, the innovating firm must seek an initial group of customers (i.e. a beachhead) within the mainstream market who will act as references for the diffusion of the new technology. As our case study illustrated, segmenting the market with respect to geographical, political, and regulatory landscapes, rather than product application realms, can be a fruitful approach. Additionally, incumbents may have more time to implement strategies to thwart disruption in CoPS industries than in mass-produced product markets, due to the slower rate of innovation in the former context, as well as the intervention of regulators that can slow down the adoption of a radically new technology. And further, the system integrator (i.e. CoPS producer) can act as a barrier to innovation if it manages the CoPS project inadequately in the face of impending regulatory restrictions, does not convince reluctant customers who see little benefit in adopting the new technology, and fails to motivate the component suppliers that display little interest in taking part. These elements bring into play a host of factors that are more emphasized in CoPS environments than in commodity product industries, such as trust, communication and coordination, and technology and knowledge transfer among partner firms. System integrators can nevertheless overcome these hurdles by providing incentives to project partners, for instance, by sharing project gains among all members of the ecosystem or project coalition.

And our fourth observation pertained to the acquisition cost of disrupting CoPS innovations that appears to be higher than that of the incumbent, the inverse of the trend witnessed in commodity industry disruptions. The competitiveness of the disrupting firm in the CoPS industry therefore derives from operational cost savings rather than the initial purchase cost (or life cycle costs). Taken together with the higher performance that the disrupting CoPS innovation delivers to the mainstream market at the time of introduction, this fourth characteristic helps complete the typology of disruptive change framework developed by Yu and Hang (2010) in their extensive review of the disruptive innovation construct (see Figure 1).

Insert Figure 1 about here

The bottom-left quadrant of Figure 1 identifies the established model of low-end disruptive change. However, Yu and Hang's review revealed two additional types of disruptive change, which were duly highlighted in their matrix. Firstly, in the upper-left quadrant are placed disruptive innovations, such as IBM's new generation of communication chips based on SiGe (silicon-germanium) technology, that demonstrate superior performance along key attributes (e.g. much higher switching speeds in the case of the SiGe-based chips) while offering lower purchase cost than the incumbent. Secondly, in the bottom-right quadrant are located high-end disruptive innovations, which refer to innovations that underperform initially but display a higher purchasing cost when first commercialized (e.g. the cellular phone), following Govindarajan and Kopalle's (2006) definition. We believe that disruptive changes in CoPS settings may help define the fourth type of disruptive innovation that Yu and Hang's original framework had left in blank. Located in the upper-right quadrant, disruptive CoPS innovations (e.g. Flash Converting technology) may demonstrate as high or higher performance than the incumbent technology, and concurrently display higher purchasing cost.

Notwithstanding this preliminary contribution of our work, we underline the inherent limitation posed by the stylized framework of a CoPS-commodity product dichotomy. We also recognize that the single case study undertaken in this paper provides evidence for our theoretical arguments rather than statistical confidence. We therefore see opportunities to continue our work both theoretically and empirically in light of these limitations. To attain a more comprehensive understanding of the disruption process in the technological landscape, in particular to characterize disruptive innovations that can complete Yu and Hang's framework, we encourage the extension of our paper to move beyond a two-classification comparison. To this end, we advocate future studies to analyze disruptive processes with respect to the various product-market dimensions that have been highlighted by scholars to distinguish CoPS from commodity products.

To illustrate our point, we consider the degree of customization in product development as one of the seminal dimensions that differentiate CoPS and commodity products. Both our theoretical review and empirical results indicate that product customization associated with a tight-knit connection between the supplier and the customer is more likely to result in the innovation satisfying the customer's performance requirement than when the connection is decoupled. The close supplier-customer interaction is likely to materialize in markets where the customer is a business that appropriates an expensive technology (i.e. B2B transaction), which is seen as an investment and therefore entails a more rational, utility seeking decision making process. The supplier is subsequently compelled to provide sufficient or higher performance with respect to traditional attributes to remain competitive or preserve the business relationship. Moreover, we argue that tailor-made products are more likely to have a heftier price tag than those which are standardized, high-volume products. This is because the nature of overall cost evaluation in B2B contexts rests in a business logic and the return that the firm can derive from an investment. Under these circumstances, it is more likely that usage costs (e.g. running, maintenance, and devaluation costs) will take center stage than the initial acquisition price (i.e. the ‘cost’ term in Yu and Hang’s framework). As a result, we propose the following hypotheses to from the focus of continuing research that strives to understand disruptive innovations marked by higher performance as well as a higher price *vis-a-vis* the incumbent technology (i.e. upper-right quadrant of Yu and Hang’s framework):

Hypothesis 1

The higher the degree of product customization, the more likely that a disruptive innovation will have higher performance and higher price in comparison to the incumbent technology.

Hypothesis 2

The lower the degree of product customization, the more likely that a disruptive innovation will have lower performance and lower price in comparison to the incumbent technology (i.e. will be a low-end disruption).

Our derived hypotheses essentially operationalize the diagonal between the lower-left and upper-right quadrants of Yu and Hang’s framework in Figure 1. In this manner, we encourage future research to test these hypotheses and concurrently extend our present paper by examining the characteristics of disruption along this diagonal axis rather than a mere comparison of two distinct categories. Different hypotheses can also be developed with respect to other product-market dimensions that scholars have addressed, such as the frequency and size of transactions, the degree of customer involvement with the supplier, the length of project durations, and the degree of superstructure involvement (e.g. governments, standards bodies, and regulatory bodies). Furthermore, we endorse successive research effort to examine a wider scope of disruption cases with respect to Yu and Hang's framework, thereby highlighting other variables that can explain the mode of disruption. Ultimately, continuing research can work towards a more comprehensive framework for both scholars and practitioners to understand links between product-market characteristics and the process of disruptive change.

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Appendix A: Figures and Tables

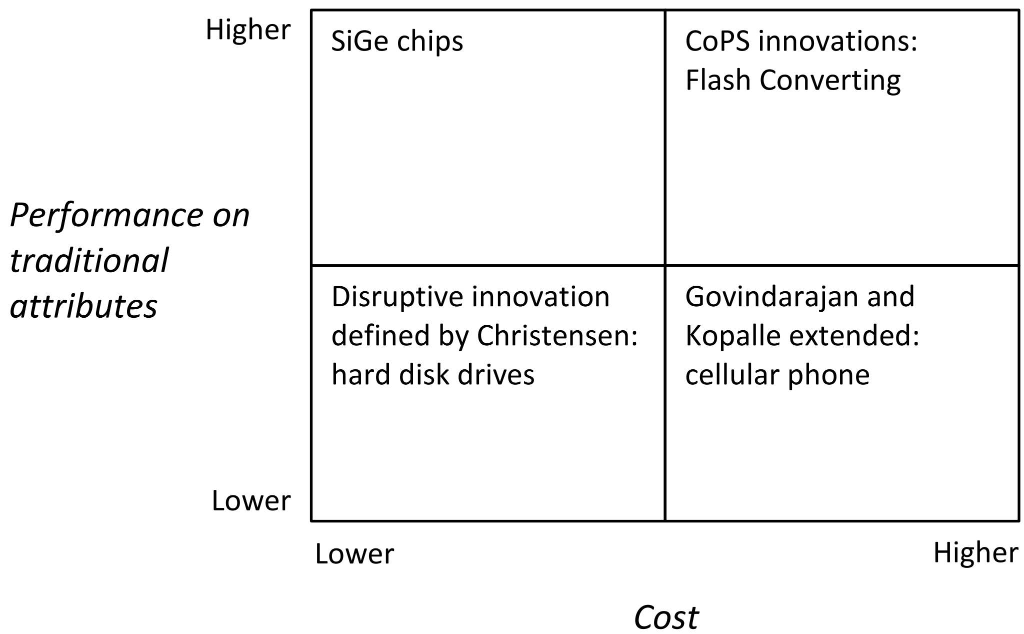

Figure 1: A framework of disruptive innovation types, based on cost and key performance dimensions (Adapted from Yu and Hang (2010)).

Table 1: Disruptive innovations in different industries

Industry	Incumbent Technology	Disruptive Technology	
automotive	compact car concept	cheap car concept	(Johnson, Christensen, & Kagermann, 2008)
banking	traditional lending practice	credit scoring technology	(C. M. Christensen, Johnson, & Rigby, 2002)
cash management	broker-mediated deal	on-line brokering	(C. M. Christensen, Bohmer, & Kenagy, 2000)
chemical	trial-and-error development	theory-based development	(C. M. Christensen, 2001)
computer	personal computer	laptop microcomputer	(C. M. Christensen & Bower, 1996)
computer memory	large hard disc drive	smaller hard disc drive	(C. M. Christensen & Rosenbloom, 1995)
computer printer	laser printer	ink-jet printer	(C. M. Christensen, Marx, & Stevenson, 2006)
computer router	voice call only router	routers capable of VoIP	(C. M. Christensen & Euchner, 2011)
computer software	large software for enterprises	simple software for SMEs	(Johnson et al., 2008)
construction	large inventory of spare parts	overnight air freight	(C. M. Christensen, 2001)
dental care	normal toothpaste	fluoristan-reinforced toothpaste	(C. M. Christensen, Cook, & Hall, 2005)
earth excavation	cable shovel excavator	hydraulic excavator	(Bower & Christensen, 1995)
education	classroom-based education	online-based education	(C. M. Christensen, Baumann, Ruggles, & Sadtler, 2006)
energy production	centralized production	decentralized production	(Hart & Christensen, 2002)
health care	doctor-provided treatment	nurse-provided treatment	(C. M. Christensen et al., 2000)
insurance	insuring corporate-employed	insuring independently employed	(C. M. Christensen et al., 2006)

Industry	Incumbent Technology	Disruptive Technology	
internet	residence-specific connection	internet connectivity kiosk	(Hart & Christensen, 2002)
microprocessor	traditional design, large scale production	modular design, minifabs	(C. M. Christensen, 2001)
microwave	fully-functional oven	energy-efficient oven	(Hart & Christensen, 2002)
motorcycle	Harley Davidson-type	affordable and humble	(Hart & Christensen, 2002)
music player	stand-alone player	integrated with content	(Johnson et al., 2008)
package delivery	price-based	speed and reliability-based	(Johnson et al., 2008)
passenger airline	full-service airline	low-fare airline	(C. M. Christensen, 2006)
pharmaceuticals	trial-and-error development	genetic technology development	(C. M. Christensen, Musso, & Anthony, 2004)
photocopying	large photocopier	small photocopier	(Bower & Christensen, 1995)
photography	photographic film processing	fully automated film processing	(C. M. Christensen, King, Verlinden, & Yang, 2008)
restaurant	traditional restaurant	fast food restaurant	(C. M. Christensen & Euchner, 2011)
retailing	department store	discount department store	(C. M. Christensen & Tedlow, 2000)
semiconductor	production in fabs	roll-to-roll production	(Hart & Christensen, 2002)
steel production	integrated steel mill	minimill	(C. M. Christensen, Kaufman, & Shih, 2008)
telephone	circuit-switching networks	packet-switching networks	(C. M. Christensen, Verlinden, & Westerman, 2002)
television	black and white television	color television	(C. M. Christensen et al., 2004)
textile	cotton spinning	synthetic fiber production	(C. M. Christensen & Bower, 1996)
travel agency	full-service agency	online travel agency	(C. M. Christensen et al., 2002)

Table 2: Copper extraction processes and flash converting as a sub-process

	mining	**comminution & froth flotation**	**flash smelting**	**flash converting**	**fire refining**
output	copper ore	copper concentrate	copper matte (copper sulfides)	blister copper (sulfur removed)	oxygen free copper
pure copper	< 0.6 %	30 %	60-70 %	98 %	100 %